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CLXXV.

(Vol. VIII.—January, 1879.)

THE FLOW OF WATER IN SMALL CHANNELS,

AFTER GANGUILLET AND KUTTER, WITH KUTTER'S DIAGRAM MODIFIED, AND GRAPHICAL TABLES WITH SPECIAL REFERENCE TO SEWER CALCULATIONS.

By R. HERING, C. E., Member of the Society.

READ OCTOBER 16TH, 1878.

One of the most interesting problems in the science of hydraulics has always been that of obtaining a correct mathematical expression for the value of the mean velocity in a stream of water. Much thought, labor and money have been expended in the search for a general formula which should give reliable results. Until recently all efforts had failed

to provide any that could be depended upon, beyond the conditions under which the observations for its deduction were made. One would be accurate only for pipes, and another only for canals in earth, still another only for large rivers with very light gradients, and so on. In the year 1869, Ganguillet and Kutter succeded, by an ingenious synthesis, in developing a new formula from the many existing reliable measurements, which is applicable under all conditions, while being at least as correct as any of the preceding ones in the cases to which they are limited.

The great importance of the degree of roughness of the wetted perimeter had been entirely overlooked until the experiments of D'Arcy and Bazin brought it into notice in 1865. In fact, Dubuat had stated that the velocity was *independent* of the material forming the perimeter. This indispensable element they now, for the first time, introduced in its full bearing into a general formula, whereby the problem of finding the mean velocity without actual experiment seems at last to have reached a somewhat satisfactory solution.

The results of these investigations were first brought to the notice of American engineers by Mr. Jackson's translation of some of Kutter's writings,* and also by a complete exhibit of his works on the subject in the Swiss Department of the Centennial Exhibition at Philadelphia in 1876.†

The formula of Ganguillet and Kutter reads as follows: §

$$v = c\sqrt{Rs} \qquad 1.$$

in which the co-efficient c is variable and determined by the equation,

$$c = \frac{y}{1 + \frac{x}{\sqrt{R}}} \qquad 2.$$

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* 1. Hydraulic Manual, by L. D'A. Jackson, London, 1875.

2. The new Formula for the mean velocity of discharge of rivers and canals, by W. R. Kutter, transl. by L. D'A. Jackson, London, 1876.

† 1. Versuch für die Aufstellung einer neuen Formel für die Bewegung des Wassers in Canälen und regelmässigen Flussstrecken. Von Ganguillet und Kutter. Aus der Zeitschrift des Oestreichischen Ingenieur und Architecten Vereins. Wien, 1869.

2. Die neuen Formeln für die Bewegung des Wassers in Canälen und regelmässigen Flussstrecken. Von W. R. Kutter. Aus der Allgemeinen Bauzeitung. Wien, 1870. Und aus dem Cultur Ingenieur. Wien, 1869 und 1870.

3. Diagram of the formula of Ganguillet and Kutter, mounted for practical use.

§ v = mean velocity.

R = mean hydraulic radius.

s = slope or tangent of inclination of the water surface.

n = co-efficient indicating the degree of roughness of the wetted perimeter.

In metric measure the two variables are,

$$y = 23 + \frac{0.00155}{s} + \frac{1}{n} \qquad 3.$$

$$x = \left(23 + \frac{0.00155}{s}\right) n$$

In English measure they are

$$y = 41.659 + \frac{0.0028075}{s} + \frac{1.8113}{n} \qquad 4.$$

$$x = \left(41.659 + \frac{0.0028075}{s}\right) n$$

As this formula is too complicated for practical use, Kutter supplemented it by a diagram which makes the solution extremely easy, as the values sought for may be read from the figure without any calculation.

The diagram at the Exhibition and also the one contained in Jackson's translation are intended to show the general application of the formula to large rivers as well as to small channels. In using it for the latter alone it is found to be rather too small for the required accuracy. Desirous of making the best use of this convenient graphical representation for obtaining the proper sizes of sewers, the writer plotted it to a large scale and confined it to grades between ∞ (vertical) and 1:2500, and to channels with a mean hydraulic radius of less than 9 feet. In this form it served the purpose much better. One inconvenience, however, was still felt when frequently used.

Kutter's diagram merely gives the values of the co-efficient c in the formula 1., but still leaves two multiplications and one extraction of a root to be made in order to find the velocity. By a simple device, this small deficiency was then supplied, allowing the mean velocity to be read off at once, with at least the same degree of accuracy as the data will warrant; namely, by considering that equation 1., may be written,

$$\frac{v}{\sqrt{R}} = \frac{c}{\sqrt{\frac{1}{s}}} \qquad 5.$$

a clue is given for the graphical construction of v. By plotting the values of c and $\sqrt{\frac{1}{s}}$ on one side and those of v and $\sqrt{R}$ on the other side of an angle, the corresponding relations will be represented by similar triangles.

In Kutter's diagram the co-efficients, c, are plotted on the vertical, the values for $\sqrt{R}$ on the horizontal axis; therefore, by graduating an additional scale of grades $\left(\sqrt{\frac{1}{s}}\right)$ on the former, and of velocities on the latter axis, the graphical solution is complete. The mean velocity of water flowing in any small channel, for any degree of roughness of perimeter and for a grade steeper than 1:2500, may be obtained in a few seconds, with a sufficient degree of accuracy and without any calculation.

This diagram, as thus completed, is herewith presented (see Plate I.), partly, because the only one generally accessible to English engineers (contained in Jackson's translation) is on a small scale, and, unfortunately, distorted so as to give values of c for smooth perimeters as much as 5 per cent. too low; partly, because the only published tables of Kutter's co-efficients, c, for English measure (contained in Jackson's Manual), which were, probably, taken from this diagram, contain the same error; and, partly, because I believe that in its modified form it may be useful to some of the members in the proportioning of small channels, sewers or pipes, and in ascertaining their true capacity when in various stages of dilapidation, and when built regardless of the value of smoothness—questions which often arise.

It is briefly described as follows: The vertical axis in the centre has the co-efficients, c, graduated on the left and the grades on the right hand side; the horizontal axis has the mean radius marked above and the mean velocity below it. To the left are four hyperbolic curves, indicating grades from ∞ to 0.04 feet per hundred, which is the limit of the diagram. They are intersected by lines radiating from a certain point, obtained by experience, equivalent to R=3.28 feet, or, by chance, one metre. These lines represent various degrees of roughness of the wetted perimeter, as noted. Commencing at the top with the smoothest surface experimented upon, being well-planed timber, they descend through gradually increasing degrees of roughness to the most irregular channels, greatly impeded by vegetation and detritus.

The construction of the diagram is, therefore, very simple. The proof of its being a correct representation of the values for Kutter's co-efficients would lead too far,* and it is merely our purpose to add the principles

* See Kutter's article in the "Zeitschrift des Oestreichischen Ingenieur und Architecten Vereins," mentioned above.

and necessary figures, by the aid of which it can be re-plotted, if required, to any scale.

Location of the points of intersection of the hyperbolas with the radial lines.—The values of y and x in Equation 2, are the co-ordinates for the hyperbolas. By substituting their values for English measure (see Eq. 4), also the grade to be indicated by the desired curve, and the value for the degree of roughness ranging from .009 to .040, as shown on the diagram, we obtain the co-ordinates of the respective points of intersection with reference to the two axes. To facilitate a plotting to any scale, or a direct calculation of the co-efficient, c, from the formula 2, the numerical values of y and x are given in Table I for four values of s, or the four hyperbolas marked "Grade Curves" on the diagram, and covering a range of grades from the vertical down to 1:2500. For convenience in using the diagram, these curves have been designated as a grade per hundred (g), instead of as the tangent of slope (s).

Co-efficients (c.)—The graduation for the co-efficients, c, is the same scale as that of the ordinates of the curves.

Grades (g).—To make the drawing as practical as possible, a value like $\sqrt{\frac{1}{s}}$ in Eq. 5, must be avoided, even at the expense of not having a regular scale, as it entails calculation. Grades are most conveniently given in feet per hundred, and they should be so plotted. If g is the grade per hundred and s the tangent of slope, then, instead of $\sqrt{\frac{1}{s}}$ we get $10\sqrt{\frac{1}{g}}$. This expression will give a quadratic scale of the reciprocals of the grade. It is now assumed that the lightest grade (g=0.04) shall coincide with the co-efficient, c=250; then, in order to locate all the grades in the scale of the co-efficients (*i. e.*, the ordinates of the hyperbolas), 250 would have to be equal to $10\sqrt{\frac{1}{0.04}} \times$ a constant, which is, therefore, 5. If we multiply all the values of $10\sqrt{\frac{1}{g}}$ by 5, we have the desired locations. Table II. contains the numerical values under the above assumption.

Mean Radii (R).—The scale by which the abscissas of the hyperbolas are plotted must be the same as the one for the values of $\sqrt{R}$. Instead of maintaining the linear scale, as Kutter has done on his diagram, sent

to the Exhibition, it was preferred to plot the values of R, giving a quadratic scale, in order to avoid the necessity of extracting a root. The location of the points, then, can be taken immediately from a table of square roots. For instance, the value $R=2$ would be plotted at a point measuring $\sqrt{2}=1.414$ from the origin in the scale of the abscissas for the hyperbolas.

Velocities (v).—In eq. 5, v is a quantity of the first degree, and its scale will, therefore, be a linear one. By substituting the values of $c=250$ and $s=0.0004$, which are located by the same point, and by selecting $R=9$, we determine the corresponding velocity as being $v=15$ feet. Then, at the point indicated by $R=9$ on the quadratic scale, or by $\sqrt{R}=3$ on the linear scale of the abscissas, we would have to mark a velocity=15 feet, *i. e.*, 5 times the value of $\sqrt{R}$; or, in other words, the same constant used in reducing the scale of grades to that of the ordinates, is likewise used for plotting the velocities in the scale of the abscissas of the curves.

For our own use we have marked off the values of R for circular sewers from 1 foot to 20 feet in diameter when running full or half full; they may serve here as an illustration. It must be remembered, as the original experiments were all made in open channels, that the formula is strictly not applicable to sewers running *full*. But, in want of further experiments, we are obliged to apply it also under this condition, and, as the results will be nearly if not exactly the same, it is safe enough to do so.

The diagram, as thus completed, contains the relation of the following 5 quantities in a practical form:

Mean velocity in feet per second.....	(v)
Kutter's co-efficient for English feet.....	(c)
Mean hydraulic radius in feet.....	(R)
Grade of water surface in feet per hundred...	(g)
Degree of roughness of wetted perimeter....	(n)

Their separate values are obtained by two operations, one giving the relation of the first four, the other that of the last four quantities.

The latter are all found on a straight line in such a manner that any three being given the fourth can be found as follows:

Given: R, g, n; Sought: c.—Join the point R on the axis of abscissas and the intersection of the line n with the curve g by a straight line.

Where it cuts the axis of ordinates will be found the proper value for c.

Given: R, c, g; Sought: n.—Join the point R, on the axis of abscissas, with the point c, on the axis of ordinates, by a straight line; prolong it until it intersects the grade curve representing g; at this point read off the value for n.

Given: c,g,n,; Sought: R.—Join the point where the radial line n intersects the curve g with the point c, on the axis of ordinates, by a straight line; prolong it down to the axis of abscissas, where it will indicate the value of R.

Given: R, c, n; Sought: g.—Join the point R, on the axis of abscissas, with the point c, on the axis of ordinates, by a straight line; prolong it until it intersects the given radial line n; here will be found the value of g, as represented by the "grade curves."

The other relation represented on the diagram is between the values for v, c, R and g, which form the terms of a proportion, and are, consequently, situated on two parallel lines in such a manner that a line joining the points indicating R and g will always be parallel to a line joining the corresponding values of v and c. Therefore, any three points being given the fourth can be readily found and the desired quantity at once read off.

The combined operation will now be as follows: Among the ten possible cases, if any three of the quantities are given, with the single exception of R, c and n (which allows g to vary as the square of v), the other two can be found on the diagram as described.

Case 1.—*Given: n=0.017, representing a channel built of good rubble masonry, g=0.06 feet per hundred, R=1.25 feet being the value for a semi-circular channel 5 feet in diameter. Sought: the mean velocity, v.*—Join the intersection of the line indicating n=0.017 with the curve corresponding to a grade g=0.06 and the point R=1.25 by a straight line (see the dotted lines on the diagram showing this example). This line intersects the axis of ordinates at a point giving a value for c of 89.6. Then place a ruler to join the point R=1.25 and the point on the axis of ordinates indicating the grade g=0.06, move it down parallelly until it intersects the value for c=89.6 as just found, and mark the intersection with the horizontal axis, where the desired mean velocity, v=2.45, is at once read off.

CASE 2.—*Given:* g=0.06, R=1.25, v=2.45. *Sought: the corresponding degree of roughness, n, indicating how smooth the perimeter must be constructed to maintain the above velocity**

The operation in this case will be reversed. Join the points marking $R = 1.25$ and $g = 0.06$ on the two axes, draw a line parallel to this through the given point $v = 2.45$, and where it intersects the vertical axis c will be found to be $= 89.6$. Then join this point c with $R = 1.25$ by a straight line, prolong it until it intersects the grade curve corresponding to $g = 0.06$, and at that point will be found the value for n (0.017), giving the greatest degree of roughness allowable to maintain the required velocity.

CASE 3.—*Given:* $R = 2.5$, $n = 0.011$ *and* $v = 5.5$. *Sought: The grade g to produce this velocity.*

Unite the points indicating $R = 2.5$ and the intersection of the line $n = 0.011$ with the grade curve, for which an approximate value must be estimated, by a straight line, and find the value of c on the axis of ordinates to be 159.5. Join this point with $v = 5.5$, and move the ruler parallelly until it intersects the horizontal axis at the value of $R = 2.5$. The desired grade can then be read off on the vertical axis, and is found to be $g = 0.0475$. Should this result deviate greatly from the value approximated for the grade curve, one repetition of the operation will always rectify it.

CASE 4.—*Given: n, g and v. Sought: R.*

Here it becomes necessary, first to approximate a value for R, in order to find one for c in the manner described before, and then, by joining c with v and drawing a parallel line through g, we intersect a truer value for R. Several repetitions will have to be made in order to get a correct result.

The other cases, which rarely occur, can be solved in a similar manner.

As to the accuracy of this graphical proceeding, we will find it to be not less than that of the data which are at our disposal. The values for R and g can of course be obtained very exactly in practice, but not those of v and n without a series of experiments. Supposing that we cannot be sure whether the roughness of the wetted perimeter in a

* To avoid confusion on the diagram in illustrating this example, the same points have been selected as in Case 1.

certain case is represented by $n = 0.010$ or $= 0.011$, which means a smoothness equivalent to plaster in pure cement or cement with one-third sand, which, with a little carelessness of workmanship in finishing, would be quite probable; or, that we cannot decide as to the amount of stones and weeds in a channel, *i. e.*, between $n = 0.028$ and $n = 0.032$, which would also be quite probable; then we can see from the diagram that the co-efficient c cannot be determined within about ten per cent. of its true value without a series of experiments. But, granting a possible error of only five per cent. on the scale of the co-efficients, we get a corresponding uncertainty of five per cent. for the velocities, resulting merely from the inability to judge of the exact value of n. The question then is: can the velocities be obtained on a chart of the scale of Plate 1 within a distance corresponding to five per cent. of their values?

The sources of error, if leaving out the inaccuracies in plotting the diagram and the unequal shrinkage of the paper, which latter may be avoided by mounting, will be: the estimating or reading of points on the scales, the uncertainty of intersections when acute, and the difficulty of ruling a long line parallel to a short one. Points on a scale may be conveniently read inside of $\frac{1}{50}''$, and for all practical cases the most acute intersections would be about 15°, making a possible error in reading from these two causes of less than $\frac{4}{50}''$, corresponding to 0.6 per cent. at the greatest velocity and to 2 per cent. at a velocity of 1 foot. The error resulting from drawing a long line parallel to a short one is greatest at 20 feet velocity. If we take an extreme case, in considering the line eight times longer, and start with an assumed maximum error of $\frac{4}{50}''$ in the short one, we get $\frac{32}{50}''$ as a possible inaccuracy in the reading of the velocity, which is still less than five per cent. With a little care, however, the ordinary values can be obtained from the diagram in its present scale within one per cent, whereas the calculated values cannot be depended upon within five per cent., except when based upon experiments for the special case in question.

In the foregoing we have a simple and reliable method for solving the general problem of the flow of water in small channels. In practice, however, two of the quantities, namely, the co-efficient c and the mean radius are not often directly considered; and we have instead usually to deal with two others, the size and discharge. Therefore, to complete the problem, we must finally get the relation of size, discharge, grade, velocity, and roughness into a practical and convenient form.

In substituting a relation for the size in place of the mean radius, we meet this difficulty; although the former defines the latter, the mean radius, conversely, will not determine the size, unless the shape of the section is also given. A general solution is therefore impossible, and it is limited at the outset by the condition that the channel in question must have a known shape, *i. e.*, either a circular, egg-shaped, rectangular, or other section. Then we may obtain its size and discharge by calculation after finding the value of the mean radius, as indicated in Case 4.

But for frequent use a far more convenient mode of obtaining the desired quantities is by means of numerical or graphical tables prepared for the required shape. A set of *numerical* tables is contained in Jackson's translation of one of Kutter's articles, already referred to. They are in metric measure for channels with straight bottoms and side slopes, and for the co-efficients $n = 0.025$, 0.030, 0.035, which are therefore only applicable to canals in earth and rivers. To prepare others for English measure for different values of n and for different shapes would entail a great amount of calculation, but it may be much reduced by applying the graphical method in such a scale as the degree of accuracy to be attained necessitates.

For almost all the ordinary cases in practice, however, *graphical* tables will be more convenient and sufficiently accurate, and it remains to be shown how they can be constructed and used.

As the above mentioned five quantities stand in a definite relation, four are variable, while the fifth remains a constant for the whole. There being fewer values for n than for any other quantity, it will be most expedient to make a table for each one of them. The discharges and grades requiring the greatest number of values to be represented ought to be graduated on the co-ordinate axes, causing the sizes and velocities to appear as curves. The size curves will all pass through the origin or zero point, as they must give a discharge $= 0$ at a grade $= 0$. The velocity curves will therefore cross them, and the co-ordinates of the points of their intersection can be determined by the following equations, if d denotes the discharge in cubic feet per second and a the area of water section:

$$d = v \times a \qquad 6.$$

$$s = \frac{v^2}{c^2 R} \qquad 7.$$

Substituting the values for the velocity and the size, we find that, in Equation 6, d will give the *ordinate* measured on the axis where the discharges are graduated, and, by Equation 7 which is another form of Equation 1, that we can obtain the value of s on the diagram, as shown above in Case 3. Remembering that the scale is marked in terms of g instead of s, we obtain at once the value needed for plotting. This value of g will be the *abscissa* of the point of intersection measured on the axis where the grades are marked. By using cross section paper, and noting the grades along the top and the discharges at the side, the two classes of curves may be readily plotted by means of these two equations.

A set of Graphical Tables, as thus developed in general, is annexed. Being intended for the ordinary requirements of sewer construction, they are confined to circular and to one form of egg-shaped sections, and are calculated for three values of n, namely, 0.011, 0.013 and 0.015, indicating the general range for good work. In Table III. are given various values of n, with reference to sewer construction, deduced from actual experiments, and also a suggestion of the degrees of roughness corresponding to the above three selected values.

Plate II. represents the relations for pipe sewers from 6″ to 36″ in diameter, Plate III. those for egg-shaped sections from 1′ 6′ × 2′ 3″ to 6′ × 9′ section, and Plate IV. those for circular sewers from 3′ to 16′ in diameter, covering the usual range of each kind. The limits of grade and discharge were regulated by the velocity which was assumed as having a practical maximum in pipes of 12′ per second, in the egg-shaped sewers of 14′ and in large circular sewers of 16′ per second.*

The plotting of these tables has been greatly facilitated, without effecting the accuracy to any practical extent, by the following considerations: In equation 4, the quotient, $\frac{.00281}{s}$, which varies with the grade, can be considered as a constant factor without making a serious

* It appears probable that the co-efficient of roughness is practically greater when the velocity is very high than when it has ordinary values. For, slight undulations in the surface, owing to imperfect construction, seem to act as additional resisting projections when passed at a high rate of speed, and thereby increase the co-efficient of roughness for the whole surface, which in turn again lowers the velocity. If we should find a theoretical velocity of twenty feet for a channel whose roughness is equal to 0.013 with ordinary velocities, it would be likely that this high velocity is not attained, but only one which would correspond to an increased roughness, perhaps to 0.015 or 0.017, according to the amount of general undulations in the surface of the work. For this reason, and because the writer has not found many reliable measurements of higher velocities, the tables were confined to the above limits.

error for the present application, and its value, which is very small for grades steeper than 1:2 500, can always be selected so that the error will be on the safe side.* Equations 4, 2 and 1 combined will then be reduced to

$$v = \text{constant} \times \sqrt{s}$$

$$\text{then also } d = \text{constant} \times \sqrt{s}$$

which indicates that the curve representing a sewer of a certain size is a *parabola*, the discharges d being the ordinates and the slopes s the abscissas. Instead of drawing a parabola for each size, we can further simplify the plotting by considering that if the abscissas are graduated in a scale of square roots, the parabola itself becomes a straight line. Then, by marking the grade, see the top of each table, so that they increase as the square roots of their values, the parabolas representing the sizes will be straight lines, as shown. A concomitant advantage is secured hereby for marking off the intersections with the velocity curves. Namely, for a constant size, $d = \text{constant} \times v$, where v varies directly as the discharge and can be graduated in a regular scale. Then we have only to calculate *one* intersection in terms of discharge and grade by means of equations 6 and 7, and then simply to proportion the others. For instance, by substituting a velocity of 16 feet and a size of 6 feet diameter, and $n = 0.011$, we find

$$d = 452 \text{ cubic feet per second,}$$

$$\text{and } g = 0.77 \text{ feet per hundred.}$$

Then, plotting this point of intersection, we draw a straight line from it to the zero point. If we desire to have a curve for every two feet of velocity, as in our tables, this line, which now represents the relations for a circular channel six feet diameter, is divided into eight equal parts, each determining respectively the intersections of the curves 2, 4, 6, etc., to 16 feet per second.

The simplicity of thus plotting these tables is apparent. They can be rapidly made on cross-section paper, in the manner designated, if desired, to suit particular circumstances, viz., to a larger scale, for other sizes, other shapes or co-efficients of roughness, for greater discharges, and when the sewer is running but partially filled.

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* The effect of this quotient is represented on Kutter's Diagram by the "Grade curves." For a channel about 13 feet in diameter, the effect of varying them for the same degree of roughness is not at all perceptible, but the smaller the diameter the greater is their influence. Then it will be safe to assume, as a constant for each size, the curve representing the *lightest* grade to which it is desired to build it.

It may be worth while to mention that in using the tables for sewers intended to carry off an amount of water equivalent to a rainfall of one inch per hour, the scale to the left indicating the discharges in cubic feet per second may also be considered as the scale of acres drained. One acre, or 43 560 square feet, would discharge $\frac{43560}{12}$ cubic feet of rain water per hour, or $\frac{43560}{12\times60\times60} = 1.0083$ cubic feet per second, therefore the scales are very nearly identical.

The use of the tables is illustrated as follows : Being on a small scale, the values obtained are not more than a close approximation, which is sufficient, nevertheless, for nearly all requirements.

1. Given : 500 acres to be drained of a one-inch rainfall, the available grade g being 0.3 per 100. Sought : the diameter of a circular sewer, built of good brickwork ($n = .013$).

On Plate IV., for $n = .013$, we find the horizontal line indicating a discharge of 500 cubic feet per second being equivalent to the drainage of 500 acres under the above assumption. Where this intersects the vertical line indicating the grade 0.3, we at once read off the requisite diameter of eight feet and a velocity of ten feet per second.

2. Given: an egg-shaped sewer 4′x 6′ section, smoothly plastered with cement mortar ($n = .011$), with a grade of .065 feet per 100, Sought : the discharge when running $\frac{2}{3}$ full.

On Plate III, for $n = 0.011$, we find that the ray indicating the size 4′x 6′ intersects the vertical line for the grade =.065 at a point showing the corresponding discharge to be 48 cubic feet, and the velocity 4 feet per second.

The tables will also give the grade and velocity by inspection, in the same manner, if the other quantities are known ; but for these other cases, it will be better to obtain the unknown quantities directly from the diagram, as shown above in Cases 1, 2 and 3.

All the known elements occurring in the problem of the flow of water in small channels, giving the results in conformity with the formula of Ganguillet and Kutter, can, therefore, be arranged in a convenient and practical form. The diagram will give the values of v, n, c and g in a few moments, and the tables, prepared for special shapes of water section will give the size and discharge at a glance, and by examining the effects of slight variations of size or grade, will enable the engineer easily to determine the most economical design.

In order to present more clearly to the eye the great importance of the degree of roughness, from an economical point of view, three sketches are added on Plate V, showing the conditions of three circular sewers of 1, 5 and 10 feet diameters running full. The ordinates denote the discharges and velocities; the abscissas, for simplicity plotted in a quadratic scale like the previous tables, indicate the grades. The pencil of rays represents various degrees of roughness from $n = .010$ to .030, *i. e.*, from a plaster of pure cement to a stony soil with a few plants. A glance at these sketches will at once show the great influence of the roughness on the discharge. A closer examination will prove that the effect increases with the smoothness of the wetted perimeter, and inversely as the size.

Therefore, the smaller the channel the better it will pay to increase the degree of smoothness to its highest practical limit. For instance, considering an open semi-circular channel 3 feet in diameter, at a grade of one foot per hundred; when built of rough rubble masonry, slightly damaged ($n = .019$), the mean velocity will be 6.2 feet per second. But when the same channel is carefully plastered with pure cement, or painted with a thick coat of natural asphalt ($n = .010$), it will give for the same grade a velocity of 13.00 feet per second, or more than *double* the discharge of the other.

The great gain in the carrying capacity of small sewers by using well laid glazed terra cotta pipes is, therefore, fully confirmed by the general formula of Ganguillet & Kutter.

Table II.

Reduction of the Scale of Grades (g) to the Scale of Co-officients (c).

Grade, per hundred (g).	Location in Scale of c. $50\sqrt{\frac{1}{g}}$	Grade, per hundred (g).	Location in Scale of c. $50\sqrt{\frac{1}{g}}$
0.040	250.000	0.21	109.110
.042	243.975	.23	104.270
.044	238.365	.25	100.000
.046	253.125	.27	96.225
.048	228.215	.30	91.285
.050	223.605	.35	84.515
.0525	218.215	.40	79.055
.055	213.195	.45	74.540
.0575	208.515	.50	70.710
.060	204.120	.60	64.550
.065	196.110	.70	59.760
.070	188.980	.80	55.900
.075	182.565	.90	52.705
.080	176.775	1.00	50.000
.085	171.495	1.25	44.720
.090	166.665	1.50	40.825
.095	162.220	1.75	37.795
.10	158.110	2.00	35.355
.11	150.755	2.50	31.620
.12	144.335	3.00	28.865
.13	138.665	3.50	26.725
.14	133.630	4.00	25.000
.15	129.100	5.00	22.360
.16	125.000	6.00	20.410
.17	121.265	7.00	18.895
.18	117.850	8.00	17.675
.19	114.705	9.00	16.667
.20	111.800	10.00	15.800

Table III.

Values of Co-efficient of Roughness (n) Deduced from Experiments.

Authority.	Description of Surface.	n =
Bazin.....	Well planed timber.....	.0096
"	Ordinary, unplaned timber.....	.0120
D'Arcy.....	Clean iron pipes.....	.0098
"	Foul " "	.0139
Kirkwood...	Tuberculated iron pipes.....	.0168
Bazin.....	Plaster of pure cement	.0100
"	" cement with $\frac{1}{3}$ fine sand.....	.0111
"	Good brick masonry.....	.0130
"	Laths nailed crosswise—0.01 meters apart.....	.0149
"	" " " 0.05 " "	.0213
"	Fine gravel well rammed, $\frac{1}{2}$ to $\frac{2}{3}$ ins. diam.....	.0170
"	Coarse " " " 1 to $1\frac{1}{2}$ ins. "	.0200
Kutter.....	New rubble, well built.....	.0145
Bazin.....	Good rubble work.....	.0170
Kutter.....	Dry rubble, slightly damaged.....	.0180
Bazin.....	Rough rubble, bed partially covered with silt and mud.	.0204
Kutter.....	Old rubble, much damaged.....	.0230

Description of Surfaces,

Suggesting the Values of n used for Graphical Tables, Plates II. to IV.

n = 0.011	Iron; cement; terra cotta pipes, well jointed and in best order; carefully plastered surface.
n = 0.013	Old iron; cement and terra cotta pipes not well jointed nor in perfect order; well laid brickwork.
n = 0.015	Foul and slightly tuberculated iron; cement and terra cotta pipes with imperfect joints, and in bad order; well dressed stonework and second-class brickwork.

AMERICAN SOCIETY OF CIVIL ENGINEERS.

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TRANSACTIONS.

NOTE.—This Society is not responsible, as a body, for the facts and opinions advanced in any of its publications.

CLXXVI.

(Vol. VIII.—January, 1879).

THE PERMANENT WAY OF RAILWAYS IN GREAT BRITAIN AND IRELAND,

WITH ESPECIAL REFERENCE TO THE USE OF TIMBER PRESERVED AND UNPRESERVED.

COMPILED FROM INFORMATION RECEIVED FROM ENGINEERS IN CHARGE OF THOSE RAILWAYS.

By JOHN BOGART, C. E., Member of the Society.

READ NOVEMBER 20TH, 1878.

The comparative economic value, for use in railway construction, of timber preserved and unpreserved, and the best methods for its preservation, have been brought before the Society at various times, and particularly at the Convention in June last. The first cost of wood will probably increase in this country in some proportion to the growth of the population, and the supply of the hard woods now generally used for railroad sleepers* will decrease, particularly in the older States.

* The cross timbers supporting the rails, and which are called *ties* in the United States, are designated *sleepers* in Great Britain. As the latter term is used by the Engineers whose experience is given in the table accompanying this paper, it will be, for convenience, also used by the writer.

The fact was known that the timber used for permanent way in Europe was in many cases treated with creosote oil or other preparations. It was also understood, that by the use of prepared timber, it was possible to employ economically some of the softer varieties of wood. The details of the experience of the European roads did not seem to be very definitely or generally known here, and, therefore, the writer prepared a letter, embodying in a series of questions most of the points upon which superior advantages had been claimed for preserved timber.

This letter was sent to the engineers of a number of the railways in Great Britain and Ireland, and full answers have been kindly returned. Many of the former individual lines of railway have been merged into one or the other of the great companies, and it is thought that these answers represent quite fairly the actual experience upon the subject. These answers are summarily presented in the table accompanying this paper.

Nearly all the lines included in this table use the double headed rail with chairs. In fact, this style of rail seems to be generally preferred wherever the traffic is heavy. Drawings of the rails, chairs and methods of attachment have been kindly sent by the engineers of several railways, and characteristic features are shown in plates VI, VII and VIII, accompanying this paper. A full-sized chair and section of rail, with key, treenails and bolt, attached to a section of a sleeper, have been forwarded by William Jacomb, Esq., Chief Resident Engineer to the London and Southwestern Railway Company, and are now in the Museum of the Society.

Most of the sleepers used in Great Britain are of Baltic red wood, and are generally 8 feet 11 inches, or 9 feet long by 10 inches by 5 inches. The gauge of the roads is 4 feet 8½ inches. The sleepers are generally rectangular. The chairs are attached to the sleepers by combined bolts and oak treenails, or by a bolt alone, generally two to each chair. The general form of treenails is shown in plate VII. They are driven through the chair bolt hole, and into a hole previously bored quite through the sleeper. A smooth round-headed iron bolt is then driven into the opening in the treenail, and forces it tightly against and into the grain of the sleeper. The base of the chair is made of quite large area to avoid cutting the tie. The rail is held in the grasp of the chair by means of a compressed oak key, sections of which are shown in the plates. The weights of the chairs are given in the accompanying table.

On one line, the North Eastern Railway, a cushion of oak is placed under the rail, between it and the chair, as is shown in plate VIII. On this line a twisted bolt is used instead of a treenail and smooth bolt.

The weight of the rails is generally about 80 pounds per yard on the lines having large traffic. The sections of rails shown in plates VI and VIII are of 80 and 82 pounds steel rails. The sleepers are generally quite covered with the ballast, as is shown in plate VI.

It will be seen from the table that the sleepers are treated with creosote oil on most of the lines from which information has been received, and that this method of preservation is the only one now in use. The cost of treating averages about 10¼ pence for each sleeper. The amount of creosote oil forced into the wood averages about 0.82 gallons per cubic foot. I am informed by manufacturers that the weight of creosote oil should be 8¾ lbs. to the gallon of 231 cubic inches; the weight of oil forced into the wood therefore averages about 7.175 lbs. per cubic foot of timber.

The life of the creosoted railway sleeper, as shown by the table, varies greatly, owing, doubtless, to circumstances of traffic, drainage, ballast, etc. The average life seems to be about 16 years, and the average gain from preservation is stated at from 2 to 10 years, averaging about 6 years.

Hard woods, as oak and chestnut, are not at all used for railway sleepers.

Samples of sleepers taken from the roadways where they had been in actual use for a number of years have been kindly forwarded to the Society, and are exhibited at this meeting. Some others have been sent, but have not yet arrived. All of these sleepers which are now here are in what seems to be a remarkably good state of preservation after a service of ten, eleven, twenty and twenty-two years. They are not decayed, are very little worn by the chairs, and have only two or three spike or treenail holes.

One sleeper is from the line of the Great Northern Railway, and has been in use from April, 1867, to October, 1877. One is from the London and South Western Railway, and has been in use 11 years. In reference to one from the North Eastern Railway, Alfred Harrison, Esq., the Engineer in charge, writes:

"It is a Scotch fir sleeper, creosoted, and was on July 29th, 1878, taken promiscuously out of half a mile that was laid down in the main line near Tweed-

mouth in June, 1858, thus having been in use for 20 years. I consider them still in a very good condition, and likely to wear other 10 years yet. They have been run over during that time by all through passenger and goods trains between London and Edinbro."

E. H. Lloyd, Esq., Divisional Engineer, sends from the line of the Great Western Railway two creosoted sleepers, and writes:

"I have sent you two sleepers which have been taken expressly out of the line near Swansea, and which have carried the heaviest traffic since the year 1857. You will observe that the sleepers are exceptionally thick and narrow, but notwithstanding these apparent disadvantages they have done their work marvellously well. This I attribute to the fact of the timber being of the very best yellow pine. They were originally 11 feet long, having been laid for the broad gauge, but in 1872, when the gauge of the South Wales line was changed, they were cut to their present lengths. I believe that these sleepers, from the length of time they have been in the line, and the very heavy nature of the traffic which has passed over them during the last 22 years, will prove most interesting instances in the economy of providing timber of the very best quality for railway work."

The writer begs to express his thanks for the full information sent by the engineers whose names are given in the accompanying table, both in replies to questions and in drawings showing the features of the permanent way of the different lines; also for the samples of sleepers taken from the roadbed as described above.

The object of this paper is simply the presentation of the facts obtained from the engineers of railway lines in Great Britain and Ireland. The table which accompanies it gives the answers just as received.

It is presented with the hope that a record of the actual experience of the life of timber in American railways may soon be prepared, and that a discussion may tend towards a solution of the question whether the time has yet come for an economic adoption of preservative processes for railroad timber in this country, upon which question there seems now to be a marked difference of opinion.